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Whole body biomechanical differences between limbs exist 9 months after ACL reconstruction across jump/landing tasks.

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Abstract

Introduction

Previous studies examining jump tasks after anterior cruciate ligament reconstruction (ACLR) have focused on performance measures without examining joint kinematic and kinetic variables. The aim of this study was to identify differences in biomechanical and performance measures between limbs across tests nine months after surgery.

Methods

Four jump tests (double leg drop jump (DLDJ), single leg drop jump (SLDJ), single leg hop for distance (SLHD) and hurdle hop (HH)) were carried out on 156 male subjects in a 3D-motion capture laboratory nine months after surgery. Statistical parametric mapping was used to identify differences in jump performance and biomechanical variables between limbs.

Results

Biomechanical measures were lower on the ACLR-side across all four tests for internal knee valgus moment (Effect Size (ES) 0.77 – 0.92), knee internal rotation angle (ES 0.59 – 0.8) and ankle external rotation moment (ES 0.59 – 0.73), with the centre of mass less posterior to the knee during the single leg tests (ES 0.61 – 0.82). The timing of the largest difference between limbs was not at the same % stance between variables within a test or for any variable across tests. Large ES differences were observed in performance in the SLDJ (ES 0.73-0.81; LSI 78%) and small differences in the SLHD (ES 0.36; LSI 94%) between the limbs.

Conclusion

Findings highlighted biomechanical differences between limbs which are consistent for jump tasks suggesting insufficient rehabilitation at 9 months post. Results indicate that the SLDJ may identify greater performance deficits between limbs than SLHD, which may over-estimate rehabilitation status.

Introduction

Anterior cruciate ligament reconstruction (ACLR) has been reported to be effective at restoring function and stability to the knee and improving patient reported outcomes [1]. However, it does not guarantee an athlete will return to play (RTP) and that re-injury will not occur [2,3]. This may be due, in part, to the absence of clear criteria identifying the completion of physical rehabilitation with respect to strength, power and biomechanics in order to successfully RTP [4]. Current RTP testing batteries often utilise performance outcomes during jumping and hopping tests (e.g. jump height, jump length) and focus on the ability to achieve the same height/distance between limbs (i.e. symmetry of performance outcome). Rarely do these clinical tests assess the biomechanics (joint angles and forces) used by the athlete to achieve this performance outcome [5-8].

Biomechanical differences between limbs after ACLR have been found in variables relating to the knee during gait, running and jumping tasks principally relating to knee extension moments and vertical ground reaction forces [9-12]. Previous research has suggested that biomechanical variables captured during double leg drop jumps (DLDJ) may predict primary anterior cruciate ligament (ACL) injury as well as secondary injury [13,14] however the primary injury analysis was in female athletes only. However biomechanical variables, both proximal and distal to the knee (i.e. ankle, hip, trunk and centre of mass (COM)), have been reported to influence the position of, and load transfer across, the knee joint during jumping and change of direction activities potentially influencing injury risk[13,15-19]. As such, the relationship between physical testing to outcomes after ACLR has been demonstrated previously [8,20-26]. Given the role of biomechanics in injury mechanism and performance, any assessment of rehabilitation status should include analysis of biomechanical variables throughout the kinetic chain, in conjunction with performance variables, to identify residual deficits to be targeted during rehabilitation.

When assessing biomechanics, discrete point analysis of the eccentric phase of landing, such as the peak knee joint moment and the knee angle at touch down, is commonly used in ACL literature [13,14,27,28]. However, discrete point analysis has been reported to omit large amounts of data thus missing potentially relevant variables and differences [29,30] which may be related to poor outcomes after RTP. In addition, peak values or peak differences between limbs may not occur at the same instant in stance thus making comparison potentially inappropriate or inconsistent between studies. The focus of ACL literature has tended to be on the eccentric phase of landing as it is the most common phase for injury, while analysis of the concentric phase might hold meaningful information when assessing rehabilitation status after ACLR. Unlike the eccentric phase, the concentric phase contains information regarding how the performance outcome is achieved – e.g. impulse momentum in ground reaction forces, which determines jump height [31]. Therefore, an analysis of movements through the entire stance phase may identify differences between limbs that can be targeted during rehabilitation to improve outcomes and suggest variables of interest for future studies analysing factors influencing outcomes, such as re-injury and performance on return to play.

The DLDJ is commonly used in ACL literature [13,14,32], yet there is conflicting evidence as to the efficacy of this movement in rehabilitation assessment to identify risk factors for ACL injury [28]. In addition, it has been suggested that a battery of tests may provide a more robust assessment of rehabilitation status than single test assessment [33,34]. Therefore, biomechanical analysis across a number of tests may be more appropriate to identify deficits between limbs. The single leg drop jump (SLDJ) is less commonly used than the DLDJ, though it may have greater ecological validity as ACL injury frequently occurs while in single leg contact with the ground [35,36]. Another commonly used assessment in RTP testing after ACLR is the distance achieved when performing a single leg hop for distance (SLHD) which has a focus on horizontal force production and absorption [9,12]. Challenging landing in the frontal plane will replicate some of the physical demands experienced in multidirectional sports and offer a different challenge to the vertical (SLDJ/DLDJ) and horizontal impulses (SLHD) in other tests [37]. As such, the analysis of a frontal plane hurdle hop, along with analysis of vertical and horizontal jumping tasks, may identify relevant biomechanical differences and deficits between the ACLR and non-ACLR limbs post-surgery.

The aim of this study was to identify biomechanical and performance variable differences between ACLR and non-ACLR limbs nine months after surgery across a number of jump tests. It was hypothesized that the 3D trunk, hip, knee and ankle joint angles and moments would be lower and COM position would be less posterior to the knee on the ACLR limb compared to the non-ACLR limb for each of the tests throughout stance phase.

Methods

One hundred and fifty-six consecutive eligible subjects were recruited prior to ACLR at the Sports Surgery Clinic, Dublin, Ireland with a mean age 24.8 years (SD +/- 4.8), height 180 cm (SD +/- 8) and mass of 84 kg (SD +/- 15.2). The average time of testing was 8.8 months (SD +/- 0.7) post-surgery. Subjects were recruited from the caseload of two orthopaedic consultants, whose practice was primarily knee surgery, from January 2014 until December 2015. Although all surgery took place at a single site, subjects underwent rehabilitation at their local rehabilitation facility and as such, a set rehabilitation program was not set across the group. Subjects enrolled as part of a longer term follow up with physical testing at 3, 6, and 9 months post operatively and via e-mail at annual follow up afterwards. This cohort study received ethical approval from University of Roehampton, London (LSC 15/122) and Sports Surgery Clinic Hospital Ethics committee (25-AFM-010).

Inclusion criteria included male, multidirectional field sport athletes with the intention of returning to the same level of participation post-surgery. Subjects were aged between 18-35 years, undergoing primary ACLR and were tested approximately nine months after surgery (8-10 months inclusive). Subjects who had multiple ligament reconstructions, previous ACL surgery, meniscal repair or those who did not intend to return to multidirectional sport after surgery were excluded from the study. All subjects had a bone patellar tendon bone graft or hamstring graft (semi-tendinosis and gracilis) from the ipsilateral side during surgery.

All testing took place in the 3D biomechanics laboratory at the Sports Surgery Clinic and written informed consent was attained before testing. An eight-camera motion analysis system (200Hz; Bonita-B10, Vicon, UK), synchronized (Vicon Nexus 1.8.5) with two force platforms (1000Hz; BP400600, AMTI, USA), captured the position of 24 reflective markers (14mm diameter) and ground reaction forces. Subjects wore their own athletic footwear while reflective markers were secured using tape, at bony landmarks on the lower limbs, pelvis and trunk per the Plug-in-Gait marker set [38]. Motion and force data were low-pass filtered using a zero-lag, fourth-order Butterworth filter (cut-off frequency of 15Hz) [39]. Standard inverse dynamics was used to calculate joint moments (reported as internal moments) at the ankle, knee and hip in all three planes using the Vicon Nexus software. All moments were normalized to body mass.

Subjects undertook a standardised warm-up: a two minute jog, five bodyweight squats, two submaximal and three maximal double leg countermovement jumps. Each subject then underwent two sub-maximal practice trials of each movement before test trials were captured. A 30 second recovery was taken between trials. Three valid attempts (i.e. maximal effort and full foot contact on force plate) were recorded for each limb with the mean results for the 3 repetitions taken for all variables. The subject's hands were placed on their hips for consistency during each of the tests and the non-ACLR limb was always tested first. The DLDJ was carried out from a 30cm step and the SLDJ was from a 20cm step. During both tests, the subject was asked to roll from the step and upon hitting the ground, to jump as high as possible while spending as little time as possible on the force plate. For the DLDJ the subject started with their feet approximately hip width apart and landed with one foot on each of the force plates. Only the first landing was included for analysis. The HH was over a 15cm hurdle, starting by standing on the leg to be tested then jumping over the hurdle towards the contralateral side and then rebound over the hurdle again to the start position. Only data from the initial landing (after first crossing of the hurdle) was used in analysis. The SLHD was a maximal horizontal jump forward to land on the force plate. Two prior efforts were used jumping off the plate to judge the starting distance for each limb. Only trials where the subject jumped onto the plate were recorded. Each of the tests were explained to the subjects in advance and they could decline being tested on any movement if they did not want, or were not able, to carry out the test. The assessor could stop testing at any point if they felt the subject could not carry out the test properly or without injury.

Custom software (MathWorks Inc, Natick, Massachusetts, USA) was used for processing and calculating additional kinematic measures capturing the relationship of trunk on pelvis and foot progression angle to pelvis in the transverse plane as well as statistical analysis. Performance variables included jump height (calculated from vertical velocity at take-off as derived using the impulse-momentum relationship), jump length (distance from heel marker at start position to landing position), ground contact time and reactive strength index (RSI) (jump height/ground contact time for drop jumps). The distance from the COM (calculated using the plug-in-gait model) to the ankle and knee joint in all three planes was calculated using the orientation of the joint in the global reference frame (Appendix A). The stance phase was defined by the ground reaction force (GRF) > 20N for the DLDJ, SLDJ and HH and for the eccentric phase only of the SLHD (from GRF > 20N until COM power = 0). Curves were normalized to 101 frames and non-linear landmark registered [40] to when vertical COM power reached zero to align the start of the concentric phase of the movement cycle across subjects to ensure an appropriate comparison of neuromuscular characteristics across limbs and participants during a continuous waveform analysis.

For the SLDJ (jump height and RSI) and SLHD (jump length), differences in performance variables between limbs were examined using a paired t-test within the statistical parametric mapping (SPM) software and limb symmetry index (LSI) was calculated by dividing the performance value of the ACLR limb by the non-ACLR limb and multiplying by 100 (SPM spm1d version M.0.4.3 (2017.01.28); http://www.spm1d.org). Between-limb differences in biomechanical variables were determined using SPM analysis (1d paired t test) over the stance phase. To determine magnitude of significant differences, Cohen's D effect size was calculated in a point-by-point manner and the mean effect size over the phase is reported (d 0.5-0.79 = medium; d>0.8 = large) [41]. Phases with significant biomechanical differences with a Cohen's D smaller than 0.5 were not reported. Differences are reported from the start to the end of the significantly different phase found using the position (in %) within the movement cycle. The % stance at which the greatest difference between limbs for each variable took place is also reported. In order to indicate the magnitude of the difference between limbs for reported variables both the mean value for each limb over the phase of difference and the mean difference between the limbs over the phase are reported. The reader is referred to the SPM plots in the supplementary information for full data on difference between limbs (Appendix B).

Results

From the 156 subjects, data was included from 147 for the SLHD, 155 for the DLDJ, 155 for the SLDJ and 156 for the HH. Subjects were excluded because of missing markers or inappropriate contact with the force plate during that given test.

Biomechanical Differences between Limbs

Double Leg Drop Jump

There were a number of differences with biomechanical variables between limbs during the DLDJ (Table 1 & Appendix B). All differences were evident during most of stance phase except for hip abduction moment, which occurred between 10-51% and 82-99% of the stance phase. The strongest differences (based on effect size) were in knee valgus moment (-0.92), knee external rotation moment (-0.81) and ankle external rotation moment (-0.80) with lower values on the ACLR side (Figure 1). Medium size differences were found for less knee internal rotation angle (-0.73), hip abduction angle (0.68), knee extension moment (0.51) and hip abduction moment (-0.50 to -0.52) on the ACLR side. There were also lower vertical (0.61) and posterior ground reaction forces (0.54) on the ACLR side. The % stance at which the maximum between-limb difference occurred for each of the variables during stance phase was not the same across the variables and occurred between 20-91% of stance.

Single Leg Drop Jump

There were a number of biomechanical differences between limbs in the SLDJ (Table 2). The largest differences (effect size) were reduced knee valgus moment (-0.74) (Figure 2) and reduced posterior COM distance to the knee (0.74) on the ACLR side throughout stance phase. There were also medium effect size differences for less knee extension angle (0.67), less hip extension angle (0.55) during end of stance phase and greater ankle dorsiflexion angle (-0.51) for most of stance phase on the ACLR side. Finally, there was less external ankle rotation moment (-0.67), knee internal rotation angle (-0.64), hip internal rotation moment (0.56) and knee external rotation moment (-0.54) on the ACLR side throughout most of stance phase. The % stance of maximum between-limb difference occurred at different percentages of the stance phase for each of the variables, from 32% to 100% of stance phase.

Single Leg Hop for Distance

There were a number of biomechanical differences between limbs in the SLHD throughout eccentric phase of landing (Table 3). Those with large effect sizes differences were less posterior COM to knee (0.82) (Figure 3) and less knee valgus moment on the ACLR side (-0.8). Medium effect size differences included less knee internal rotation (-0.61) less hip abduction angle (0.6), hip internal rotation moment (0.59), ankle external rotation moment (-0.59) and ankle eversion moment (-0.51) on the ACLR side. There was also less dorsiflexion angle on the ACLR side (-0.5) and less knee flexion (-0.55) throughout landing. The % stance of greatest difference was inconsistent between variables but was more frequent in the latter half of the eccentric part of landing (42%-100%).

Hurdle Hop

The hurdle hop had the fewest number of variables with between-limb differences but these variables were common with all the other tests (Table 4). These include less knee valgus moment (-0.74) (Figure 4), less ankle external rotation moment (-0.59), and less knee internal rotation angle (-0.59) on the ACLR side. In addition, the COM was more anterior to the knee (0.61) on the ACLR side. The % stance of maximum difference between variables was spread from 26% to 57% stance phase.

Jump performance differences between limbs

The DLDJ jump height was 23.8cm (+/- 4.8) and RSI was 0.83 (+/-0.25). Overall results for the single leg jumps including mean, standard deviation and 95% CI are reported (Table 5). There were significant differences between limbs ($p < 0.001$) for height jumped and RSI in the SLDJ with large effect sizes and distance jumped for the SLHD with a small effect size. LSI for the SLDJ was 79% (+/- 21%) and 78% (+/- 34%) for the jump height and RSI respectively and 94% (+/- 19%) for the SLHD.

Discussion

This study identified biomechanical differences between limbs throughout the kinetic chain during DLDJ, SLDJ, SLHD and HH tests 9 months after ACLR. Between-limb differences in internal knee valgus moment, knee internal rotation angle and ankle external rotation moment were reported for all the tests. In the sagittal plane the COM position relative to the knee was different between limbs for all the single leg tests. The percentage of stance when the difference between limbs was greatest was not the same between variables and tests across both the concentric and eccentric phases. Findings demonstrated that the between-limb effect size difference was greater for the SLDJ jump height than for the SLHD jump distance.

Biomechanical Differences Between Limbs

Between-limb biomechanical differences were found through the kinetic chain and at different phases of the movement cycle during each of the examined jump tests. There were a number of variables, which indicated significant between-limb difference in all of the tests. These differences during stance are potentially due to insufficient restoration of function after surgery. Internal knee valgus moment was lower in the ACLR limb across all the jumps and was consistently the variable with the largest effect size. External knee valgus moment (internal varus moment) has been suggested to be a predictor variable in ACL injury [13,14]. However in this study the subject group demonstrated an internal knee valgus moment in all tests throughout nearly all of stance phase. Despite the absence of external knee valgus moment the difference between limbs in frontal plane moments, with lower internal valgus moments on the ACLR limb, may leave the limb more susceptible to external valgus moments on return to play in an open environment suggesting incomplete rehabilitation and potential injury risk.

Knee internal rotation angle was different between-limbs in all tests with less internal knee rotation (tibia internally rotated relative to femur) on the ACLR limb. The largest effect size difference was reported in the DLDJ. Knee rotation has been shown to influence ACL strain in cadaver studies with reduced internal rotation reducing ACL strain [42]. Ankle external rotation moment was also different between limbs for each of the tests (lower values on the ACLR side). This moment may result from, or may contribute to, the rotation asymmetries seen at the knee joint as they are coupled movements.

Asymmetry of knee extensor moments has been suggested to be a risk factor for second ACL injury [43] and knee extensor strength deficits are commonly found on the ACLR side [44]. Extensor asymmetry was evident in this cohort in the DLDJ where the ACLR limb had lower knee extension moments between 6-88% and lower vertical ground reaction force between 5-99% which suggests an unloading of the limb. Similar findings have been reported in knee extension moments and vertical ground reaction forces during DLDJ testing 9 months after ACLR, with hip and ankle variables compensating for the knee[45]. Knee extension moment deficits during SLHD have been reported previously 6 months post ACLR, but there was no between-limb difference for knee extension moment for the single leg tests in this study though the COM was moved closer to the knee in the sagittal plane in them all. This may have been accomplished through trunk, pelvis or hip flexion or maintaining a more extended knee position, as seen in the SLHD, thus reducing the demand on the knee extensors by shortening the extensor moment arm [12,46]. The reduced extensor capacity on the ACLR side was also evident in the single leg drop jump where there was significantly less hip and knee extension angle during the latter stages of push off highlighting that deficits between limbs are evident throughout stance phase and suggest insufficient or incomplete rehabilitation that may have a negative influence on outcomes and performance after ACLR.

A one-dimensional data analysis technique, SPM, was used to assess the between-limb differences in joint angles and moments over the full duration of the stance phase of the tests. Past research has focused on specific discrete magnitudes/times points, for example at initial contact, peak GRF or at maximum knee valgus, to assess the athlete's ability to absorb momentum in landing (Hewett et al., 2005, Kristianslund et al., 2013, Paterno et al., 2010). However, this method of analysis is vulnerable to type I error by failing to assess large portions of the stance phase [30]. Maximum differences may not occur at a specific point in stance or during the eccentric or concentric phase of the jump only, therefore SPM allowed the study hypotheses to be explored appropriately. The study demonstrated that the maximum difference between joint variables occurred at different % of stance phase within a test and at different % stance for the same variable between tests. For example, peak knee valgus moment occurred at 25% of ground contact time for the DLDJ, 68% for the SLDJ, 42% for the SLHD (equivalent of 21% in rest of tests as eccentric phase only) and 56% for hurdle hop. This suggests it may be more appropriate to analyse variables across waveforms rather than at preordained discrete points, for example at initial contact or within the first 10% of landing to ensure appropriate comparison between limbs and variables and identify potentially relevant differences throughout stance phase.

Performance Differences Between Limbs

Jump height and jump distance tests were included as they are commonly included in rehabilitation and RTP protocols to assess rehabilitation status after ACLR. The results of this study supported the hypothesis that there would be a between-limb difference in the jump performance of the single-limb tests. Despite the fact that the SLHD is more commonly used in ACLR testing literature[47], it demonstrated differences with only small effect sizes between the two limbs compared to the large effect sizes evident in the SLDJ. In addition, the LSI between limbs for the SLHD was > 90%, thus reaching appropriate levels in RTP [8,20] whereas the LSI for the SLDJ was <80% LSI for both jump height and RSI. This supports previous findings that commonly used ACLR tests are not equivalent and may not identify functional deficits after reconstruction [48].

Limitations

This study investigated differences in performance and biomechanics between limbs for a battery of jump tests. The study was carried out on a specific cohort of subjects potentially limiting the generalizability of the findings to other groups such as female athletes and those not involved in multidirectional sports. The analysis of biomechanical variables across the kinetic chain in a battery of jump tests creates the potential that "over-analysis" may occur (i.e. carrying out analysis on multiple tests and variables thus finding significant differences that may not be relevant). However, this paper is exploratory in nature as there is an absence of research examining differences throughout the stance phase and across a number of tests within the same cohort of subjects. The inclusion of medium and large effect size differences only, attempted to identify only those differences of largest magnitude to highlighting variables of greatest clinical and research interest despite the multiple analyses. The study findings are not related back to outcomes after ACLR such as re-injury, RTP and ongoing knee pain or how values compare to healthy uninjured subjects so the influence of findings is as yet unknown. Future research should prospectively focus on the relationship between biomechanical differences at 9 months post ACLR and the aforementioned outcomes to enhance rehabilitation and RTP outcomes.

Conclusion

This study demonstrated biomechanical differences throughout the kinetic chain, and performance differences between limbs nine months post ACLR. Biomechanical differences were found between limbs with lower internal knee valgus moments, ankle external rotation moments and knee rotation angles on the ACLR side for much of the stance phase for all the tests. The position of the COM was less posterior to the knee on the ACLR side on the single leg tests. The % stance phase of the maximum difference between limbs was different between variables and tests across both the concentric and eccentric phases, suggesting analysis of the entire waveform is important for appropriate comparison of function between limbs after ACLR. Results suggest that the SLDJ may identify greater jump height/length deficits between limbs than SLHD, which may over-estimate rehabilitation status. These findings demonstrate the importance of including biomechanical analysis through stance phase during assessment of jump tests after ACLR.

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Conflicts of Interest

There are no known conflicts of interest.

Perspectives

Differences in jump height performance between limbs is commonly used as a measure of rehabilitation status after ACL reconstruction without assessing the biomechanics of how that jump was performed. Where biomechanical analysis has been undertaken it has focused on a single joint or plane and examined a single point in time, potentially missing important information for the clinician. The results from this study demonstrate consistent biomechanical differences across the entire kinetic chain for the four jump tests. These differences occurred throughout stance phase with the maximum difference between limbs different for each variable and each test supporting the analysis of whole body movement throughout the entire stance phase after ACL reconstruction. The biomechanical differences were consistent between tests despite differences in limb symmetry of jump height/length with the SLHD potentially over-estimating rehabilitation status. The findings support the use of 3D biomechanical analysis of whole body movement in addition to jump performance in the assessment of rehabilitation status after ACL reconstruction, and identifies specific biomechanical differences between limbs 9 months after surgery that could be targeted during rehabilitation to potentially influence re-injury risk.

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Table 1 Biomechanical differences between limbs during double leg drop jump

Variable	Effect Size	Start	End	Direction	Mean ACLR Side (+/- SD)	95% CI	Mean Non ACLR Side (+/- SD)	95% CI	Mean Difference (+/- SD)	95% CI	Instant	Max Difference (+/- SD)	95% CI
Knee Moment Frontal (Nm/kg)	-0.92	6	89	Valgus (+)	6.4 (2.5)	5.6 to 7.1	13 (3.9)	12 to 14	-6.6 (6.2)	-6.88 to -6.38	25	-6.8 (6.4)	-7.1 to -6.57
Knee Moment Transverse (Nm/kg)	-0.81	0	97	External Rotation (+)	0.2 (0.4)	0.02 to 0.4	1.6 (0.6)	1.3 to 1.8	-1.4 (1.8)	-1.43 to -1.28	20	-1.4 (1.7)	-1.45 to -1.35
Ankle Moment Transverse (Nm/kg)	-0.79	0	97	External Rotation (+)	1.7 (1.1)	1.4 to 1.9	4 (1.9)	3.6 to 4.3	-2.2 (2.3)	-2.38 to -2.14	27	2.6 (2.7)	-2.73 to -2.44
Knee Angle Transverse (º)	-0.73	0	100	Internal Rotation (+)	15.9 (2.1)	14.4 to 17.4	23.9 (2.1)	22.2 to 25.5	-8 (10.6)	-8.17 to -7.89	27	-9.6 (11.1)	-9.7 to -9.4
Hip Angle Frontal (º)	0.68	0	92	Abduction (-)	-4.1 (0.9)	-3.3 to -4.8	-7.6 (0.8)	-6.9 to -8.4	3.6 (6)	3.55 to 3.6	64	5.1 (7.2)	5.08 to 5.18
Vertical Ground Reaction Force (N/kg)	-0.61	5	99	Vertical (+)	12 (2.3)	11.6 to 12.3	14.2 (2.6)	13.8 to 14.6	-2.2 (2.1)	-2.21 to -2.17	80	-2.2 (1.8)	-2.29 to -2.18
A-P Ground Reaction Force (N/Kg)	0.54	17	91	Posterior (-)	-0.56 (0.3)	0.5 to -0.65	-1 (0.3)	-0.9 to 1.1	0.42 (0.4)	0.41 to 0.42	78	0.4 (0.4)	0.38 to 039
Knee Moment Sagittal (Nm/kg)	-0.51	6	88	Extension (+)	15.5 (4.3)	14.7 to 16.3	19.6 (4.9)	18.7 to 20.6	-4.2 (5.7)	-4.26 to -4.1	31	-5.6 (7.5)	-5.77 to -5.41
Hip Moment Frontal (Nm/kg)	-0.52	10	51	Abduction (+)	1.1 (1.8)	0.4 to 1.7	3.8 (2.3)	3.1 to 4.6	-2.8 (4.3)	-2.8 to -2.75	17	-3.6 (5.1)	-3.6 to -3.56
Hip Moment Frontal (Nm/kg)	-0.50	82	99	Abduction (+)	1 (1.6)	0.6 to 1.4	2.8 (1.8)	2.4 to 3.3	-1.8 (2.6)	-1.86 to -1.8	91	-2.4 (3.3)	-2.45 to -2.42

The table reports variables that were different between limbs with an effect size d>0.5 from the SPM analysis. It reports the % of stance over which the difference occurred (start/end), the mean value across the identified phase for that variable with standard deviations and 95% CI and the average effect size difference across the reported phase. Nm/Kg – Newton-meters/Kilogram; N/Kg – Newtons/Kilogram; SD - standard deviation; 95% CI - 95% Confidence Intervals; Instant - % stance phase at which difference between the two limbs was greatest; start/end –beginning/end % stance phase when the difference was greatest between limbs.

Table 2 Biomechanical differences between limbs during a single leg drop jump

Variable	Effect Size	Start	End	Direction	Mean ACLR Side (+/- SD)	95% CI	Mean Non ACLR Side (+/- SD)	95% CI	Mean Difference (+/- SD)	95% CI	Instant	Max Difference (+/- SD)	95% CI
Knee Moment Frontal (Nm/kg)	-0.74	4	87	Valgus (+)	13.4 (3.4)	12.4 to 14.3	20 (4.3)	18.9 to 21	-6.5 (7.5)	-6.7 to -6.49	68	-8.8 (9.5)	-8.95 to -8.63
COM to Knee Sagittal (mm)	0.74	0	87	Posterior (-)	-20.7 (5.5)	-16.7 to -24.5	-41.2 (5.3)	-37.7 to -44.7	20.5 (26.6)	20.1 to 20.9	53	26.4 (30)	25.4 to 27.3
Knee Angle Sagittal (º)	0.67	92	100	Flexion (+)	11 (2.2)	10.1 to 11.9	7 (2.5)	6.1 to 7.8	4 (5.7)	3.97 to 4.06	100	5.7 (5.9)	-8.16 to -8
Ankle Moment Transverse (Nm/kg)	-0.67	6	85	External Rotation (+)	4.1 (1.5)	3.6 to 4.5	6.6 (1.9)	6.1 to 7.1	2.5 (3.6)	-2.63 to -2.43	47	-3.9 (5.4)	-4.06 to -3.73
Knee Angle Transverse (º)	-0.64	0	96	Internal Rotation (+)	17.1 (2.2)	15.6 to 18.5	23.8 (2)	22.2 to 25.5	-6.8 (11.5)	-6.93 to -6.62	53	-8.1 (12.8)	-8.16 to -8
Hip Moment Transverse (Nm/kg)	0.56	0	79	Internal Rotation (-)	-3.8 (0.7)	-3.5 to -4	-5 (0.9)	-4.7 to -5.3	1.3 (2.1)	1.21 to 1.29	42	2.3 (3.5)	2.21 to 2.3
Hip Angle Sagittal (º)	0.55	85	100	Flexion (+)	19.5 (2)	18.4 to 20.6	15.6 (2.5)	14.5 to 16.6	4 (5.5)	3.88 to 3.97	100	6.1 (5.9)	5.87 to 6.28
Knee Moment Transverse (Nm/kg)	-0.54	0	86	External Rotation (+)	1.4 (0.6)	1.2 to 1.7	2.6 (0.8)	2.3 to 2.9	-1.1 (2.5)	-1.19 to -1.06	68	-1.7 (3.5)	-1.8 to -1.6
Ankle Angle Sagittal (º)	-0.51	0	91	Dorsiflexion (+)	14 (1.9)	13.1 to 14.9	17.2 (1.9)	16.3 to 18.1	-3.2 (4.7)	3.97 to 4.06	52	-4.3 (5.9)	-4.3 to -4.28

The table reports variables that were different between limbs with an effect size d>0.5 from the SPM analysis. It reports the % of stance over which the difference occurred (start/end), the mean value across the identified phase for that variable with standard deviations and 95% CI and the average effect size difference across the reported phase. Nm/Kg – Newton-meters/Kilogram; mm – millimeters; SD - standard deviation; 95% CI - 95% Confidence Intervals; Instant - % stance phase at which difference between the two limbs was greatest;; start/end –beginning/end % stance phase when the difference was greatest between limbs

Table 3 Biomechanical differences between limbs during a single leg hop for distance

Variable	Effect Size	Start	End	Direction	Mean ACLR Side (+/- SD)	95% CI	Mean Non ACLR Side (+/- SD)	95% CI	Mean Difference (+/- SD)	95% CI	Instant	Max Difference (+/- SD)	95% CI
COM to Knee Sagittal (mm)	0.82	0	100	Posterior (-)	-103.7 (5.8)	-98 to -103.8	-133.7 (7.2)	-128.5 to -138.9	30.5 (29.8)	30.4 to 30.5	100	40.2 (35.3)	39.4 to 41
Knee Moment Frontal (Nm/kg)	-0.80	22	100	Valgus (+)	17.2 (1.7)	15.9 to 18.5	25.3 (2.1)	23.8 to 26.9	-8.1 (10.4)	-8.4 to -7.9	42	-10.2 (12.3)	-10.6 to -9.8
Knee Angle Transverse (º)	-0.61	0	100	Internal Rotation (+)	15.1 (2.8)	13.6 to 16.6	21.7 (2.9)	20 to 23.4	-6.6 (9.9)	-6.8 to -6.47	100	-8.2 (11.8)	-8.38 to -8.09
Hip Angle Frontal (º)	0.60	29	100	Adduction (+)	2.3 (1.1)	1.4 to 3.3	-1.3 (0.9)	-0.4 to -2.2	3.6 (6.6)	3.6 to 3.64	66	4.2 (6.7)	4.16 to 4.2
Angle Moment Transverse (Nm/kg)	-0.59	24	100	External Rotation (+)	0.33 (0.5)	0.1 to 0.6	1.4 (0.6)	1.1 to 1.7	-1.1 (2.1)	-1.14 to -1.02	81	-1.3 (2.4)	-1.4 to -125
Hip Moment Transverse (Nm/kg)	0.59	3	100	Internal Rotation (-)	-4.2 (1)	-3.9 to -4.8	-5.9 (1.1)	-5.5 to -6.2	1.6 (2.9)	1.61 to 1.68	55	2.4 (4)	2.33 to 2.51
Knee Angle Sagittal (º)	-0.55	9	100	Flexion (+)	46.7 (3.5)	45.2 to 48.3	52.2 (3.2)	50.8 to 53.6	-5.4 (6.4)	-5.32 to -5.52	100	-7.9 (8.4)	-7.69 to -8.21
Ankle Moment Frontal (Nm/kg)	-0.51	11	100	Inversion (-)	-0.17 (0.41)	-0.46 to 0.1	0.83 (0.46)	0.5 to 1.2	-1 (2.7)	-1.04 to -0.96	82	-0.96 (2.5)	-0.97 to -0.95
Ankle Angle Sagittal (º)	-0.50	0	100	Dorsiflexion (+)	4.9 (2.5)	3.9 to 5.8	8.7 (2.2)	7.7 to 9.6	-3.7 (4.4)	-3.75 to -3.78	100	-5.1 (5.7)	-5.15 to -5.07

The table reports variables that were different between limbs with an effect size d>0.5 from the SPM analysis. It reports the % of stance over which the difference occurred (start/end), the mean value across the identified phase for that variable with standard deviations and 95% CI and the average effect size difference across the reported phase. Nm/Kg – Newton-meters/Kilogram; mm – millimeters; SD - standard deviation; 95% CI - 95% Confidence Intervals; Instant - % stance phase at which difference between the two limbs was greatest; start/end –beginning/end % stance phase when the difference was greatest between limbs.

Table 4 Biomechanical differences between limbs during a hurdle hop

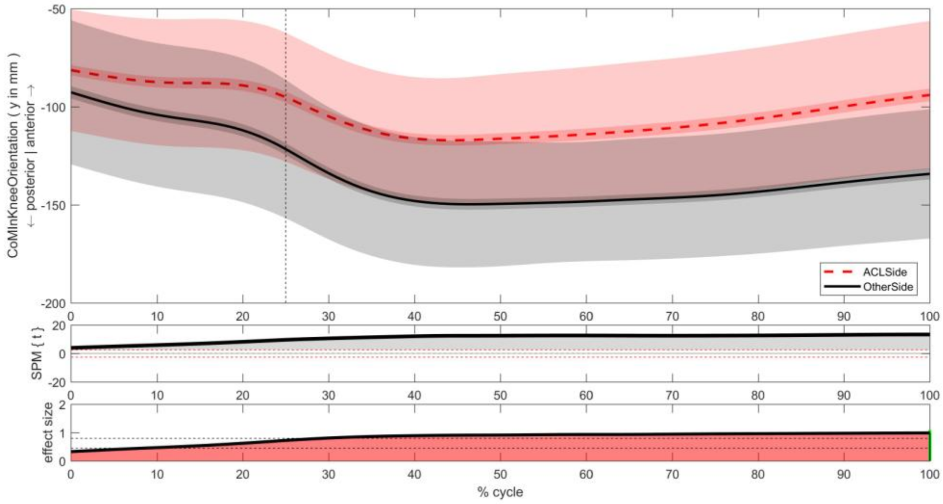
Variable	Effect Size	Start	End	Direction	Mean ACLR Side (+/- SD)	95% CI	Mean Non ACLR Side (+/- SD)	95% CI	Mean Difference (+/- SD)	95% CI	Instant	Max Difference (+/- SD)	95% CI
Knee Moment Frontal (Nm/kg)	-0.74	17	81	Valgus (+)	13.9 (2.8)	12.8 to 15	20.6 (3.3)	19.4 to 21.8	-6.7 (8.5)	-6.79 to -6.61	56	-10.2 (12.5)	-10.2 to -10.1
COM to Knee Sagittal (mm)	0.61	0	95	Anterior (+)	12 (5.9)	8.7 to 15.3	-3 (5.1)	-6.2 to 0.3	15 (23.6)	14.9 to 15	26	17.6 (25.2)	17.6 to 17.6
Knee Angle Transverse (º)	-0.59	0	100	Internal Rotation (+)	16.5 (2.1)	15 to 18	22.8 (2.3)	21.2 to 24.5	-6.3 (11.1)	-6.51 to -6.13	57	-7.7 (12.9)	-7.87 to -7.59
Ankle Moment Transverse (Nm/kg)	-0.59	18	79	External Rotation (+)	5.9 (1.3)	5.3 to 6.4	8.3 (1.6)	7.7 to 8.9	-2.4 (4.1)	-2.5 to 2.4	45	-3.4 (5.7)	-3.55 to -3.37

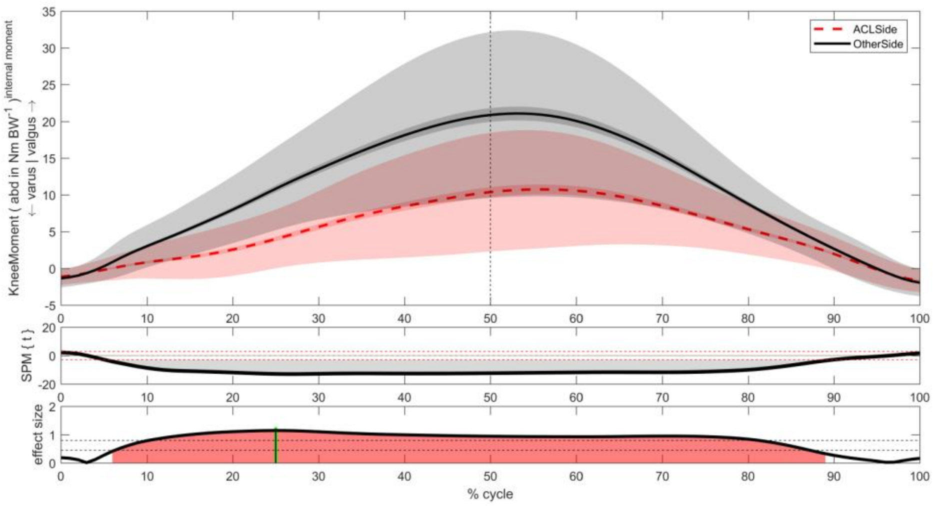
The table reports variables that were different between limbs with an effect size d>0.5 from the SPM analysis. It reports the % of stance over which the difference occurred (start/end), the mean value across the identified phase for that variable with standard deviations and 95% CI and the average effect size difference across the reported phase. Nm/Kg – Newton-meters/Kilogram; mm – millimeters; SD - standard deviation; 95% CI - 95% Confidence Intervals; Instant - % stance phase at which difference between the two limbs was greatest; start/end –beginning/end % stance phase when the difference was greatest between limbs.

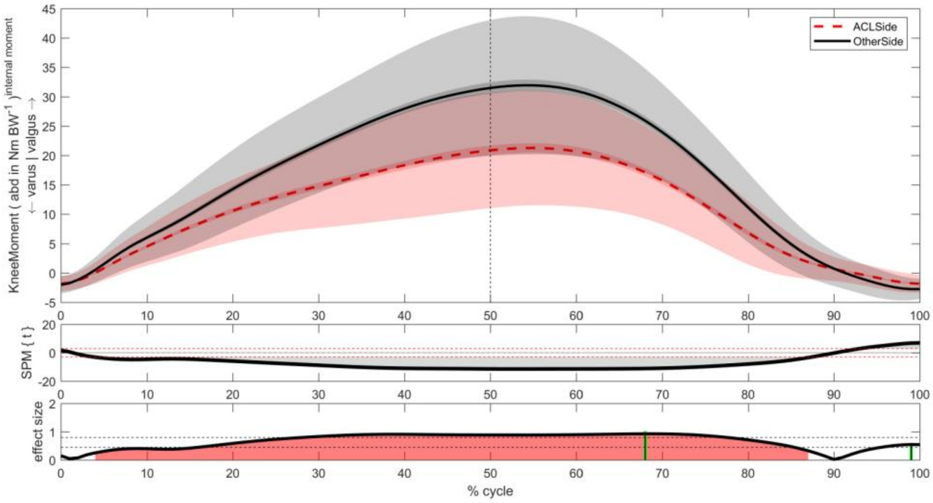
Table 5 Jump performance results for single leg drop jump and single leg hop for distance

	Effect Size	Mean ACLR Side (+/- SD)	95% CI	Mean Non ACLR Side (+/- SD)	95% CI	LSI (+/- SD)
Single Leg Drop Jump						
Height (cm)	-0.81	10.8 (3.3)	10.2 - 11.35	13.7 (3.2)	13.2-14.2	79% (21)
Reactive Strength	-0.73	0.31 (0.12)	0.29-0.32	0.4 (0.13)	0.38-0.42	78% (34)
Single Leg Hop						
Distance (cm)	-0.36	141.4 (26.1)	137 - 145.8	150.5 (23.8	146.5 - 154.5	94% (19)

cm – centimeter; CI – confidence interval; SD – standard deviation; LSI – limb symmetry index


CoMInKneeOrientation (y in mm)
← posterior | anterior →
ACLSide
OtherSide
SPM { t }
effect size
% cycle


KneeMoment (abd in Nm BW^{-1})$^{internal\ moment}$
← varus | valgus →
ACLSide
OtherSide
SPM { t }
effect size
% cycle



ACLSide
OtherSide
KneeMoment (abd in Nm BW-1)internal moment
← varus | valgus →
SPM { t }
effect size
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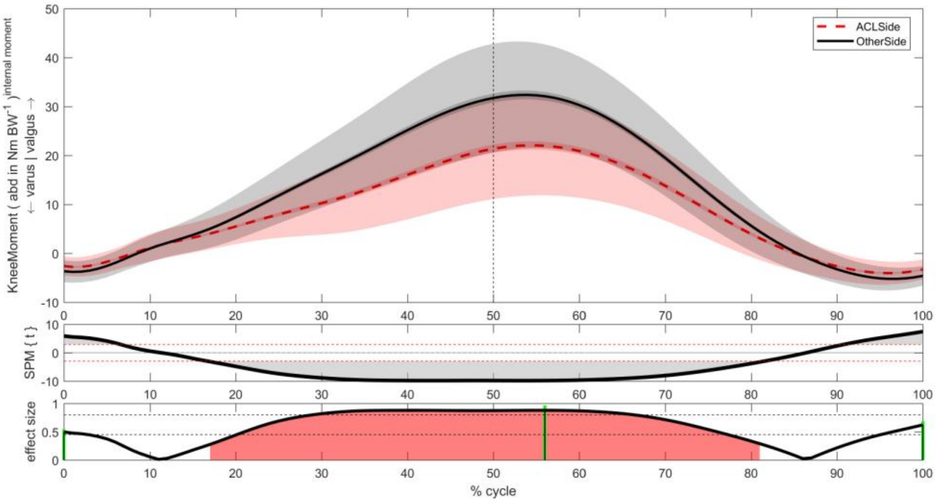
ACLSide
OtherSide
KneeMoment (abd in Nm BW^{-1})$^{internal\ moment}$
← varus | valgus →
SPM {t}
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